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A Simple Finnish Method for the Structural Fire Design of Composite Structures

Timo Inha[1]

Abstract

The structural fire design of composite structures in Finland has previously been based on furnace tests, which are expensive and take too much time to arrange. With the increasing prominence of composite constructions and steel constructions, it has thus been necessary to evolve a simple calculation model for their structural fire design.

While the Finnish method is akin to those involving reductions, the concept of 'reduction' should be understood in a different sense from that implied in Eurocode 4, for example. In order to obtain a simple basis for manual calculations, the cross-section is transformed to contain parts having only constant material properties. For this purpose a reduction in the size of the cross-section has to be made.

The method is based partly on tabulated data and partly on calculation, the size of the cross-section being determined first from tabulated data, after which the fire temperatures of the parts of the steel section and the reinforcing bars are determined from tabulated data or from the temperature distribution of concrete cross-section.

Finally, the flexural resistance, shear resistance and other properties needed can be checked easily employing a reduced concrete cross-section with material properties equal to those prevailing at + 20 °C, reduced parts of a steel section with material properties equal to those prevailing at the appropriate fire temperatures and reinforcing bars with material properties equal to those prevailing at their fire temperatures.

[1]LichTech, Division of Structural Engineering, Tampere University of Technology, P.O. Box 600, SF-33101 Tampere, FINLAND

Introduction

A composite construction usually includes three parts, a hot-rolled steel profile, a concrete section and reinforcing bars, and it is necessary to take account of variations in the material properties of all three. Although the structural steel profile and reinforcing bars may belong to the same category of steel, they seem to possess different material properties according to the official regulations existing in Finland. Structural fire design requires knowledge of the variations in more than three material properties if the composite construction includes a cold-formed steel section, high strength concrete, light weight concrete or prestressed strands.

The structural fire design of composite structures is similar to the design of steel structures or concrete structures, depending on whether the steel section needs fire protection or not. When no fire protection is required, composite structures are designed in the manner of concrete structures, taking into account the varying material properties of the structural parts and/or reducing the cross-section or its parts. When fire protection is required for the steel section, its critical temperature, protection material and thickness are determined.

Design methods

The design methods can be classified as entailing four systems:

1. Design employing tabulated data (Tabulated Data)
2. Simple calculation model
3. General calculation model
4. Official approval based on furnace tests

Design according to Tabulated Data requires a knowledge of the minimum cross-sectional dimensions, minimum concrete cover for the steel section and minimum axis distance from the reinforcing bars to the exposed surface, all of which are given in the tables for different fire resistance classes. The tabulated data are valid only for standard fire conditions.

When using the simple calculation model, parts of the cross-section are reduced and varying material properties with respect to temperature are used. The temperature distribution of the cross-section can be determined for composite columns or beams using the equivalent temperature distribution of the concrete cross-section, and for composite slabs by means of simple formulae which allow for the insulating air gap between the thin steel sheet and the concrete, i.e. thermal expansion will separate the steel sheet from the concrete section immediately after initiation of the exposure to fire.

When using the general calculation model, the temperature distribution of the cross-section is determined according to the required fire resistance class and design fire condition, which can

be either the standard fire or a compartment fire.

The temperature distribution of the cross-section can be determined using available temperature curves or suitable computer programs. Designing for a compartment fire requires the use of a computer program to determine the temperature distribution.

The resistances of a composite structure are calculated employing material properties determined according to temperatures. Restraining forces are considered if applicable.

Material properties

The effects of temperature on the strength and modulus of elasticity of hot-rolled steel and cold-formed steel according to the Finnish Recommendations are shown in Fig. 1.

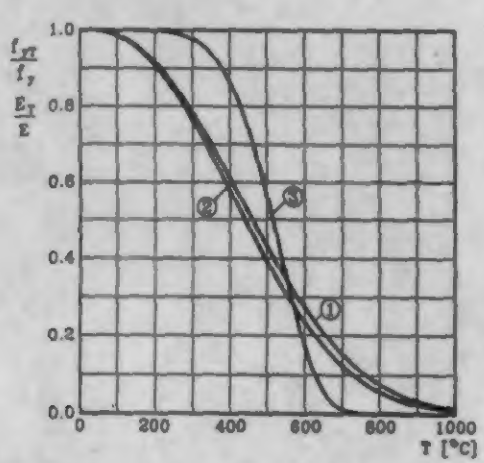

Figure 1. Strength and modulus of elasticity of structural steel according to the Finnish Recommendations, plotted relative to the temperature.
(1) Strength plot for hot-rolled steel, (2) Strength plot for cold-formed steel, (3) Modulus of elasticity plot for structural steel.

The concrete section possesses its own load bearing capacity inside a composite structure and simultaneously serves as fire protection for the steel section. The effects of temperature on the compressive strength of normal concrete and high strength concrete, as employed in the Finnish Recommendations, are shown in Fig. 2.

Ribbed bars are always used as longitudinal bars or stirrups in

the concrete sections of composite members, in some cases only to prevent spalling of the concrete. In concrete-filled hollow sections, the bars are usually required as longitudinal reinforcement, because the exposed steel section loses its strength rapidly during fire.

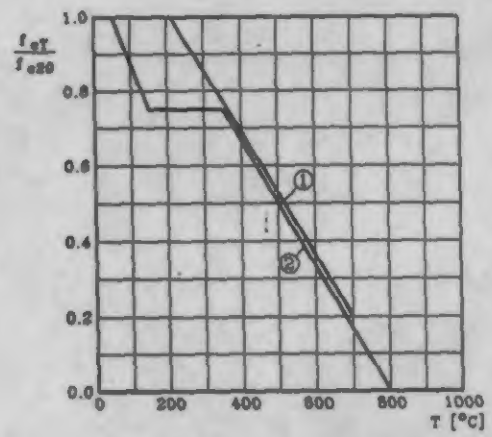

Figure 2. Compressive strength of concrete according to the Finnish Recommendations, plotted relative to temperature.
(1) Normal concrete plot, (2) High strength concrete plot.

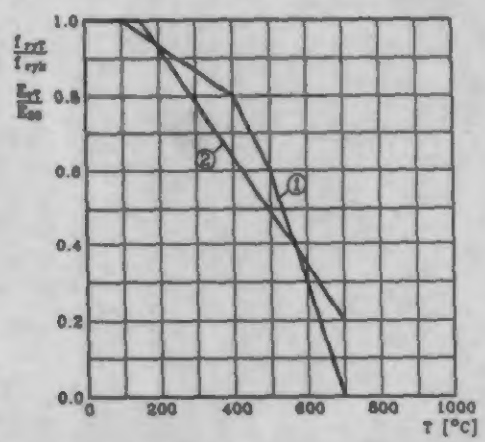

Figure 3. Strength and modulus of elasticity of reinforcing steel according to the Finnish Recommendations, plotted relative to temperature. *(1) Strength plot, (2) Modulus of elasticity plot.*

The effects of temperature on the strength and modulus of elasticity of reinforcing steel according to the Finnish Recommendations are shown in Fig. 3. The design curves are different from those of structural steel.

Reduction of cross-section

The simple calculation model is based on reduction of the cross-section. The structural cross-section is divided into parts, some of which are reduced, while others can be assumed to have a constant temperature determined for the section.

The exposed, unprotected part of a structural steel section can be usually taken into account if the fire resistance class does not exceed 30 minutes.

The reduction of a concrete section influences the dimensions of the compressed section and the shear resistance of the active cross-section, and is not the same for a concrete-filled hollow tube as it is for a concrete-encased steel section, as there is always a considerable moisture content in hollow sections which will delay the increase in temperature and moreover will promote dangerous spalling.

The strength and modulus of elasticity employed for the reduced concrete section are equal to those prevailing at + 20 °C, as are the material properties employed for the reduced steel parts if the temperature of the concrete surrounding them is approximately + 20 °C. Otherwise, the average temperature of the steel parts can be determined according to the temperature distribution of the corresponding concrete cross-section, for example.

The cross-sectional areas of the reinforcing bars are not reduced, and their strength and modulus of elasticity are determined directly with respect to their temperature. The temperature in the bars may be derived according to their axis distance from the exposed concrete surfaces, e.g. by reference to the temperature distribution of the corresponding concrete cross-section.

If only one side of the concrete slab or wall is exposed to fire, the values for the depth reduction made to a compressive concrete cross-section are given for the different fire classes in Table 1. The corresponding values for the width reduction $b_o - b_{oT}$ and the effective depth reduction $d_o - d_{oT}$ in a rectangular concrete cross-section for concrete-encased or partially encased steel profiles are given in Table 2, and those for the width reduction $b_o - b_{oT}$ and the depth reduction $h_o - h_{oT}$ in a rectangular concrete cross-section for concrete-filled hollow steel profiles in Table 3. Values are given only for the fire resistance classes 30 - 120 minutes, as no furnace test results exist for concrete-filled hollow sections over periods of more than two hours. The values for the length reduction $h - h_T$ in a

particular part of a steel section perpendicular to an exposed surface (see Fig. 5b) are given in Table 4.

The reduction in the diameter of a circular concrete cross-section may assume values equal to those of the depth reduction $d_o - d_{oT}$ or $h_o - h_{oT}$ in a rectangular concrete cross-section given in Table 2. or 3. while the unreduced diameter of the cross-section is taken to be equal to the width b_o of a rectangular cross-section.

Reduction values for points intermediate between those given in Tables 1. - 4. may be calculated by linear interpolation.

Table 1. Values for the depth reduction $h_o - h_{oT}$ of a concrete slab or wall for different fire classes when only one side is exposed to fire.

	FIRE RESISTANCE CLASS [min]					
	30	60	90	120	180	240
$h_o - h_{oT}$ [mm]	10	15	25	35	50	60

Table 2. Values for the width reduction $b_o - b_{oT}$ and effective depth reduction $d_o - d_{oT}$ of a rectangular concrete cross-section for different fire classes when three sides of the cross-section are simultaneously exposed to fire. The effective depth reduction values are given with respect to the width b_o.

	FIRE RESISTANCE CLASS [min]					
	30	60	90	120	180	240
$b_o - b_{oT}$ [mm]	20	30	50	70	100	120
$d_o - d_{oT}$ [mm] when b_o [mm]						
80	5	50	-	-	-	-
180	5	20	35	65	-	-
280	5	20	25	35	55	65
380	5	20	25	35	50	65
480	5	15	20	30	45	60
≥ 580	5	15	20	30	40	55

Table 3. Values for the width reduction $b_o - b_{oT}$ and de... reduction $h_o - h_{oT}$ of a rectangular concrete cross-sect... of a concrete-filled hollow steel tube for different ... classes when all sides of the cross-section ... simultaneously exposed to fire. The depth reduct... values are given with respect to the width b_o. The wi... reduction values can be employed only when the dep... h_o is more than 100 mm larger than the width ... Otherwise, the width reduction is taken to represent ... depth reduction.

	FIRE RESISTANCE CLASS [min]			
	30	60	90	120
$b_o - b_{oT}$ [mm]	10	20	50	70
$h_o - h_{oT}$ [mm] when b_o [mm]				
100	10	80	-	-
200	10	30	70	120
300	10	30	55	85
≥ 400	10	25	50	80

Table 4. Length reduction $h - h_T$ in different fire classes for th... part of a steel section located perpendicular to th... exposed surface. If the steel part is the flange of ... partially encased I-section residing below a continuou... concrete slab across the beam section where th... reduction is to be performed, the tabulated values mus... be multiplied by 0.6. If only one side of the steel part ... e.g. a hollow tube on which the reduction is to b... performed, is against the concrete, the tabulated value... must be multiplied by 1.5.

TEMPERATURE AT THE BOTTOM FACE OF THE STEEL SECTION NEAREST TO THE EXPOSED SURFACE	FIRE RESISTANCE CLASS [min]					
	30	60	90	120	180	240
UNLIMITED	30	60	80	100	140	180
600 °C	20	30	40	50	60	70
500 °C	15	20	30	40	50	60
400 °C	10	15	20	30	40	50
300 °C	5	10	15	20	30	40
200 °C	0	5	10	15	20	30
100 °C	0	0	0	0	0	0

...ms

...Composite beams may be classified into four categories, as ...wn in Fig 4.

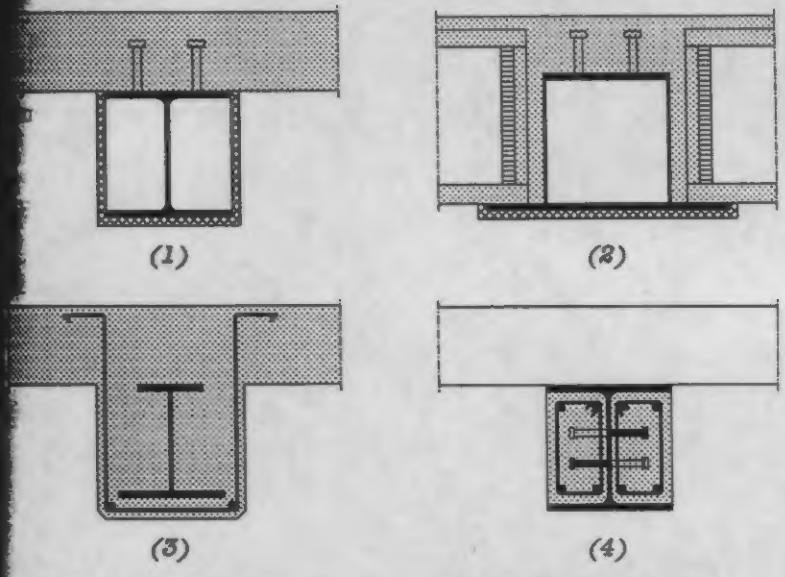

Figure 4. Categories of composite beams.
(1) Concrete slab overlapping a steel section
(2) Partially concrete-encased profile
(3) Totally concrete-encased profile
(4) Concrete-encased steel web. No shear connection between concrete slab and steel member.

Structural fire design of the composite beams shown in Fig. 4 may be performed employing the simple calculation model, as emphasized in Example 1 below.

Example 1.

The procedure for structural fire design is shown step by step for the case of a composite beam containing a partially encased profile, i.e. belonging to the second category in Fig. 4. Let the composite beam be of one of the kinds shown in Fig. 5.

1. The structural steel parts residing outside the concrete cross-section may be designed to have some or no fire protection. If there is to be protection, the design temperature and the corresponding material properties

are determined. The design temperature for any section should not usually exceed 600 °C. The unprotected parts of the sections are normally ignored as having any structural fire resistance.

2. The appropriate steel parts inside the concrete cross-section are reduced in the manner shown in Fig. 5 a. (web) and Fig. 5 b. (web and top flange). The values for the reductions are given in Table 4. The material properties of the reduced steel sections are determined according to their average temperature.

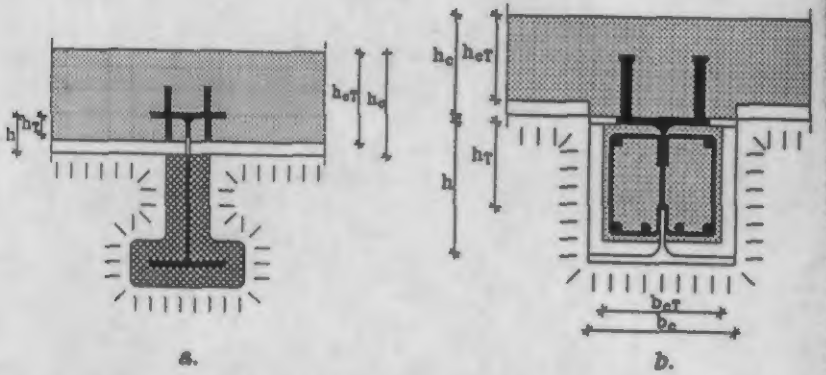

Figure 5. Partially encased profiles, in which the blank parts denote the areas reduced.

3. The concrete cross-section is reduced according to the values given for a slab in Table 1 and a beam in Table 2, employing material properties at + 20 °C.

4. The maximum temperatures of the reinforcing bars and stirrups are determined according to the temperature distribution of the concrete cross-sections in which they are located and their strengths are calculated accordingly.

5. The position of the neutral axis is determined from the reduced parts of the cross-section and the varying material properties.

6. The flexural resistance M_{uT} and shear resistance V_{uT} are checked. If $M_{uT} < M_T$ or $V_{uT} < V_T$, the design temperature of the structural steel parts outside the concrete is reduced and/or the cross-sectional area of the concrete encasing the steel is increased and/or a greater area for the reinforcing bars is added. The design

procedure is then restarted at step 1, 2, 3 or 4.

7. The deflection is checked. If the deflection f_T does not exceed L/30, L being the span length , no more exact analysis of the beam is required.

8. The fire protection material for the structural steel parts outside the concrete cross-section is chosen and its thickness determined according to the design temperature of the steel part and the required fire resistance class.

Columns

Composite columns may be classified into four categories, as seen in Fig. 6.

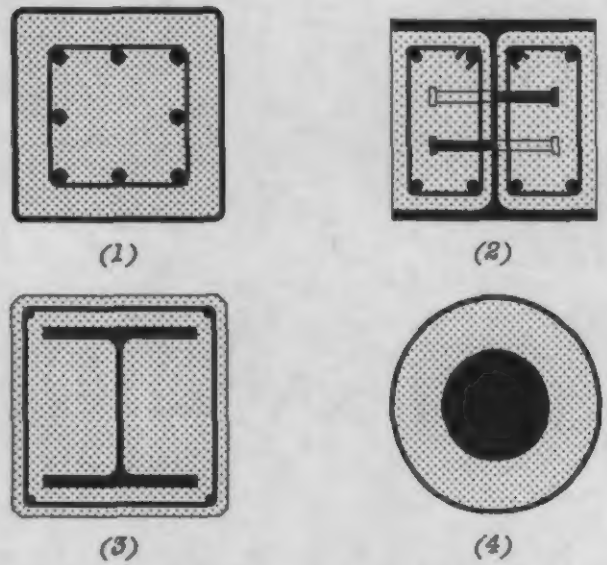

Figure 6. Classification of composite columns.
(1) Concrete-filled hollow section
(2) Concrete-encased steel web
(3) Concrete-encased steel section
(4) Concrete-filled hollow section including steel core.

The structural fire design of composite columns as shown in Fig. 6 may be carried out by means of the simple calculation model, as illustrated in Example 2.

Example 2.

The structural fire design procedure for a composite column having a concrete-filled hollow section, as presented here, falls to the first category in Fig. 6. The cross-section of the column is shown in more detail in Fig. 7.

1. The steel section exposed to fire is ignored, as shown in Fig. 7.

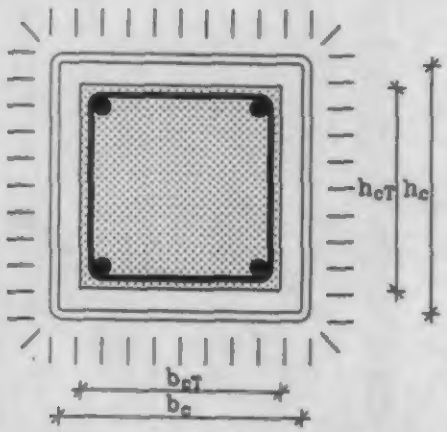

Figure 7. Concrete-filled steel section, in which the blank parts are considered to be ineffective.

2. The area of the concrete cross-section is reduced in the manner given in Table 5, employing the material properties at + 20 °C.

3. The temperatures in reinforcing bars are determined with respect to their axis distances from the nearest fire-exposed surfaces and the fire resistance class required. If no more exact methods are available, the temperature distribution of a concrete cross-section equal in size to the original column section may be used as a basis for an approximative method, i.e. when determining the temperatures for the bars, the total cross-section, including the steel area is assumed to consist of concrete.

4. The load carrying capacity of the column is then determined as that of a reinforced concrete column having a cross-section reduced as explained above.

Slabs

Composite slabs may be classified into two main categories: non-protected and protected. The former usually need additional reinforcement unless the profiled steel sheet is partially protected by concrete. The types of non-protected composite slab are shown in Fig. 8. Fire protection for composite slabs insulated against fire from below is designed in the form of either a protective coating underneath the profiled steel sheet or a suspended ceiling, as shown in Fig. 9.

The fire resistance class of composite slabs without an additional reinforcement or fire protection cannot usually be set at higher than 30 minutes.

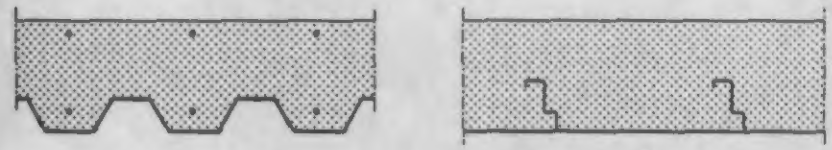

Figure 8. Non-protected composite slab.
a. Additional reinforcement
b. Structural protection.

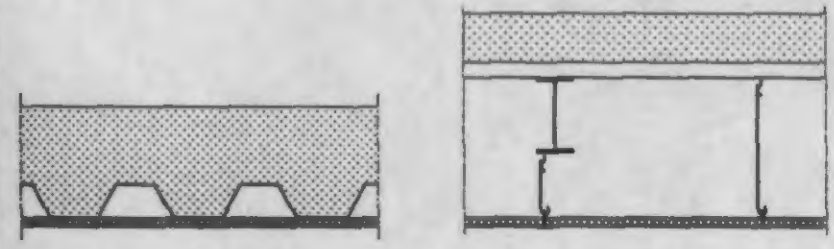

Figure 9. Protected composite slab.
a. Insulating coating
b. Suspended ceiling.

The effective thickness of the slab, h_s, is the main variable determining its ability to serve as a compartment boundary, for which h_s is given in Equation (1).

The effective slab thickness h_s according to the Finnish Recommendations is given for different fire resistance classes in Table 5.

$$h_e = h_c + 0.5 \cdot h_s \cdot (L_1 + L_2)/(L_1 + L_3), \quad (1)$$

where

h_c, h_s, L_1, L_2 and L_3 are the cross-sectional dimensions of the slab as given in Fig. 10.
$h_c > 50$ mm
$h_s = 1.5 \cdot h_c$, if $h_s/h_c > 1.5$

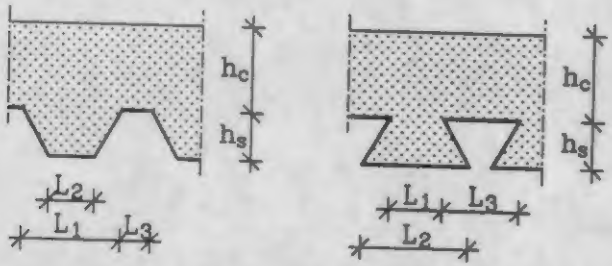

Figure 10. Cross-sectional dimensions of composite slabs for insertion into Equation (1).

Table 5. Minimum effective thickness h_e required for composite slabs in different fire resistance classes.

	FIRE RESISTANCE CLASS [min]					
	30	60	90	120	180	240
h_e [mm]	60	80	100	120	150	175

Temperatures in reinforcing bars may be determined from the formulae given in Table 6. If the temperature distribution of the concrete cross-section only, without the effect of sheeting, is used as a basis for the temperature evaluation the design values may become erroneously high.

Table 6. Formulae for the temperature evaluation of reinforcing bars inside a composite slab in different fire resistance classes according to Eurocode 4. Fire exposure is assumed to be the standard fire according to ISO 834. The factor γ is given in Equation (2).

STANDARD FIRE DURATION [min]	TEMPERATURE T_s OF REINFORCING BAR [°C]
30	$T_s = 900 - 350\gamma \leq 500$ °C, $\gamma \leq 2{,}5$
60	$T_s = 1175 - 350\gamma \leq 800$ °C, $\gamma \leq 3{,}3$
90	$T_s = 1285 - 350\gamma \leq 880$ °C, $\gamma \leq 3{,}6$
120	$T_s = 1370 - 350\gamma \leq 930$ °C, $\gamma \leq 3{,}8$

$$1/\gamma = 1/\sqrt{u_1} + 1/\sqrt{u_2} + 1/\sqrt{u_3} \quad (2)$$

where

u_1, u_2 and u_3 are the distances from the reinforcing bar to the profiled steel sheet as specified in Fig. 11.

Figure 11. Geometry for positioning the reinforcing bar.

Structural fire design for non-protected composite slabs may be carried out by assuming the slab to be of the reinforced concrete type, having its bottom surface in the shape of the sheet profile.

The size of the concrete cross-section is reduced while retaining the existing form of the slab. The reduction values are given in Table 1, and the material properties at + 20 °C are those given for a reduced concrete cross-section.

The ultimate temperature of a reinforcing bar is determined according to Table 6, from which its the strength may be calculated.

The flexural resistance and deflection may be determined from the effective slab section as explained above (i.e. concrete + reinforcing bars).

Conclusions

The calculation model explained here is versatile and serve well for manual design purposes where one cannot afford to spend time on more detailed analysis. Structural decisions based on these methods have been found to be reliable enough:

- The method seems to be conservative, for beams, in a range of 10 % relative to more exact methods of calculation,
- the margin of conservativeness for columns relative to Eurocode ranges from 0 to 10 %,
- identical results to those of Eurocode are obtained for slabs.

Eurocode 4 and ECCS Technical Note 55 present data for the resistance of a limited number of composite columns having only a specified cross-section as a function of the buckling length, which is also limited to a maximum of 5 metres.

The Finnish method is not restricted to any particular cross-section or steel shape, and the buckling length is not restricted. The method has been compared with the results of furnace tests carried out in Germany (8 loaded tests performed at Braunschweig for Rautaruukki), and the calculation yields acceptably conservative results for all cases.

The method of Eurocode 4 even allows for the unprotected, fire-exposed flange of a partially encased I-beam in structural fire design, independent of its temperature. This should not be allowed for indiscriminately, however, and the Finnish method omits it entirely.

The strength of the web material is considered in Eurocode 4 to be a function of the assumed temperature distribution, which is not practicable in manual calculations. In the Finnish method a given part of the web is taken to be ineffective and the temperature at which the strength of the rest of the web is defined assumes a certain constant value.

Eurocode 4 defines the compressive strength in the concrete flange as the cylinder strength, while in Finland 70 % of the cube strength is allowed for, which is considerably lower.

Temperature distributions for selected beam profiles have been determined in furnace tests carried out in Sweden and Finland, and it has been found that slightly conservative results are obtained as compared with these when using the reduction method.

No reduction method is presented in EC4 for determining the negative bending resistance in composite slabs, but instead temperatures in the compressed concrete are defined inside layers 5 mm apart, and this is liable to make determination of the compressive stress resultant elaborate.

When employing the Finnish method the designer reduces a constant strip of the fire-exposed, compressed concrete following the profile shape in order to able to employ a stress block having its strength defined according to 20 °C.

There are good reasons to believe that the method is conservative, since the depths to be reduced are in accordance with those expressed in Eurocode 2 for solid concrete slabs. Furthermore, one should bear in mind that an isolating air cap will develop between the steel sheet and the concrete during a fire which will then retard the increase in temperature inside the concrete as compared with the solid fire-exposed concrete.

In Finnish model reduction is applied to all structural parts of the cross-section in order to be able to determine constant properties for the parts considered effective. This is essential in order to maintain the method as characterized in the headings: simple.

APPENDIX

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